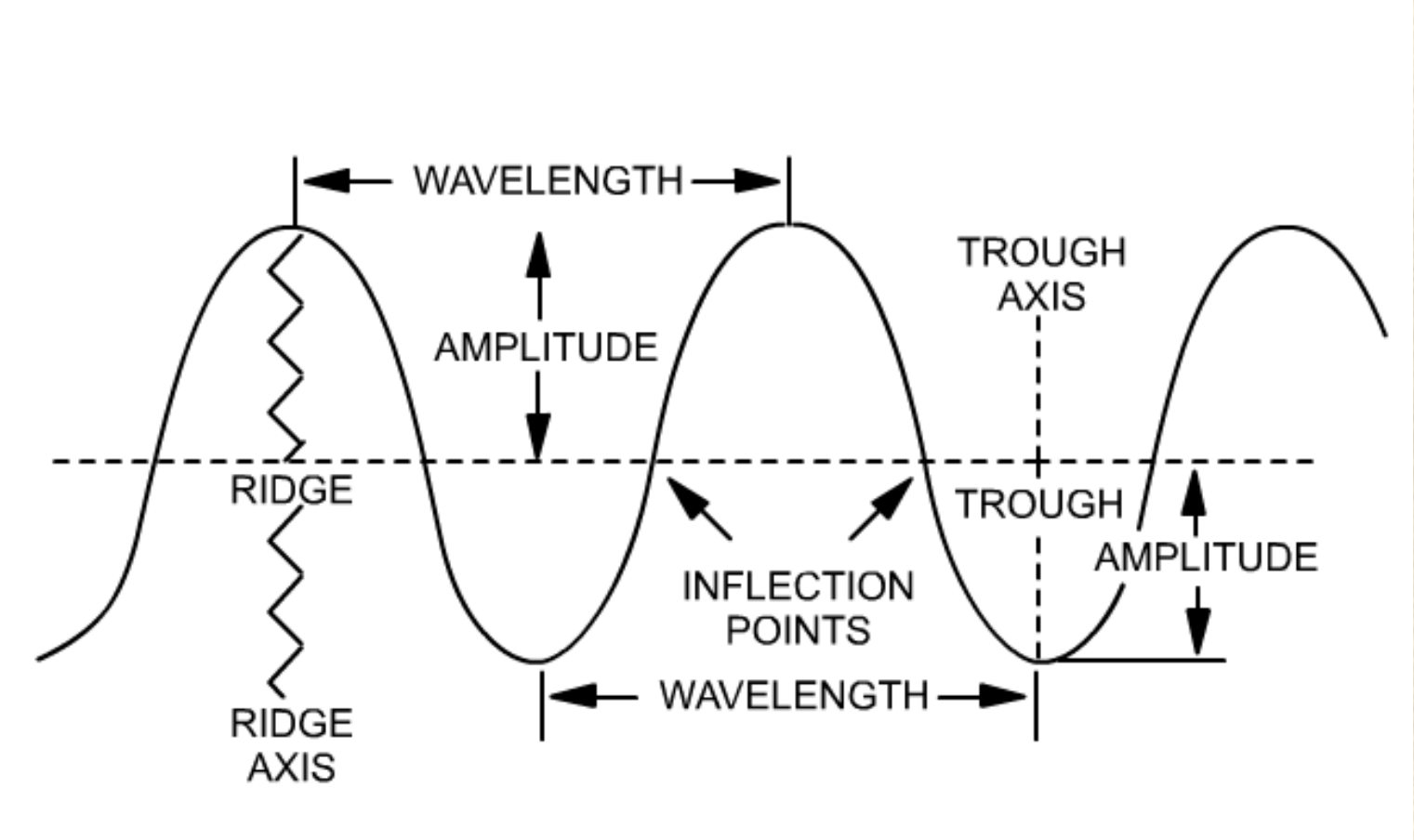
Atmospheric Dynamics I

f. Determine the characteristics that depict a certain wave type in the upper-level circulation.

Atmospheric wave terminology

- Ridge
  - Elongated area of relatively high atmospheric pressure or heights
  - Associated with anticyclonic turning of height (or pressure) contour pattern and wind flow.
  - Associated with lower values of vorticity.

Atmospheric wave terminology.



Atmospheric wave terminology

- Ridge Axis
  - Line of maximum anticyclonic turning in height (or pressure) contours and wind flow
  - Elongated axis of maximum pressures or heights.
  - Associated with vorticity minimum.

Atmospheric wave terminology

- Trough
  - Elongated area of relatively low atmospheric pressure or heights
  - Associated with cyclonic turning of height (or pressure) contour pattern and wind flow.
  - Associated with higher values of vorticity.

Atmospheric wave terminology

- Trough Axis
  - Line of maximum cyclonic turning in height (or pressure) contours and wind flow
  - Elongated axis of minimum pressures or heights.
  - Associated with vorticity maximum.

Atmospheric wave terminology

- Inflection Point
  - Point between
    - A ridge and a trough
    - Curvature changes from anticyclonic to cyclonic or vice-versa.
    - Air parcels at this point would be in straight line flow.

Atmospheric wave terminology

- Wavelength
  - The distance from:
    - Ridge axis to ridge axis, or
    - Trough axis to trough axis, or
    - Inflection point to inflection point
  - The preferred meteorological practice is to use the segment between two adjacent ridges, so that the trough is in the middle of the wavelength.

Atmospheric wave terminology

- Amplitude
  - Distance from inflection point to
    - crest of ridge, or
    - base of trough
  - One half the distance between crest of ridge and base of trough.
  - Measured parallel to ridge or trough axes.

Atmospheric wave terminology

- Wave amplification theory (developed from the height tendency equation (not shown; based on quasi-geostrophic (QG) theory discussed later in Dynamics I.
  - Wave amplification on the synoptic scale is dependent on the variation of temperature advection with height (assumes QG flow as defined later).

Atmospheric wave terminology

- For synoptic scale mid-latitude systems, temperature advection normally maximizes in the lower troposphere near the top of the boundary layer. If we assume the magnitude of temperature advection decreases with altitude upward through the middle and upper troposphere, then the following relationships apply:
  - Warm advection in the lower troposphere forces heights to rise in the middle and upper troposphere. Warm advection into a:
    - » Ridge causes the heights to rise, and the ridge to amplify (i.e. deepen)
    - » Trough causes the heights to rise,and the trough to deamplify (i.e. dampen)

Atmospheric wave terminology

- Cold advection in the lower troposphere forces heights to fall in the middle and upper troposphere. Cold advection into a:
  - Ridge causes the heights to fall and the ridge to deamplify. (i.e. dampen)
  - Trough causes the heights to fall and the trough to amplify. (i.e. deepen)

Atmospheric wave terminology

- As discussed in the following section, wave speed is partially a function of wave size; thus, changes in the amplitude of a wave can affect its motion. Waves with:
  - Larger amplitudes generally move slower
  - Smaller amplitudes generally move faster

Atmospheric wave terminology

- Wave speed
  - Distance wave moves in given amount of time.
  - Usually measured in nautical miles per hour (knots).

Atmospheric wave terminology

- Wave speed theory:
  - Wave speed is dependent on two major influences (assumes quasi-geostrophic flow; discussed in a later section)
    - Speed of the flow in which the wave is embedded.
      - » Strong westerly component of wind = faster wave movement.
      - » Weak westerly component of wind = slow movement.

Atmospheric wave terminology

- Vorticity advection
  - » Recall that absolute vorticity (η) equals the sum of relative vorticity (ζ) + planetary vorticity (f): $\eta = \zeta + f$
  - » Thus η advection = ζ advection + f advection

Atmospheric wave terminology

- Positive η advection (PVA) causes the height of an isobaric surface to fall) (i.e. 500 mb height falls)
- Negative η advection (NVA) causes the height of an isobaric surface to rise (i.e. 500 mb height rises)

Atmospheric wave terminology

- In longwaves, generally spanning more than 10,000 km, f advection is much greater than ζ advection; thus the "sign" of the f advection determines whether η advection will be
  - + (PVA→ falling heights) or
  - - (NVA → rising heights)

Atmospheric wave terminology

i. In northwesterly flow upstream of the trough axis, f advection is positive (wind is blowing from higher toward lower values of f). Thus PVA produces height falls upstream (west) of the trough.

Atmospheric wave terminology

ii. In southwesterly flow downstream of the trough axis, f advection is negative (the wind is blowing from lower toward higher values of f). Thus NVA produces height rises downstream (east) of the trough

Atmospheric wave terminology

iii. Height falls west of the trough axis and height rises east of the trough axis force the trough to “retrograde” westward against the flow.

Atmospheric wave terminology

- In much shorter waves (I.e. shortwaves), ζ advection is much greater than f advection; thus the "sign" of the ζ advection determines whether η advection will be:
  - + (PVA→ falling heights) or
  - - (NVA→ rising heights)

Atmospheric wave terminology

i. In southwesterly flow downstream of the shortwave trough axis, ζ advection is positive. Thus PVA produces height falls downstream (east) of the trough, allowing the trough to prograde eastward.

Atmospheric wave terminology

ii. In northwesterly flow upstream of the trough axis, ζ advection is negative. Thus NVA produces height rises upstream (west) of the trough, allowing the trough to prograde eastward with the flow.

Atmospheric wave terminology

iii. Height falls east of the trough axis and height rises west of the trough axis force the trough to “prograde” eastward with the flow.

Atmospheric wave terminology

- Wavelength/Wave Speed relationships.
  - Larger wavelengths = slower wave movement
  - Smaller wavelengths = faster wave movement.

Atmospheric wave terminology

- Wave phase relationships
  - Height contour wave-wave relationships
    - Waves of different lengths and amplitudes are often horizontally super-imposed on one another in the atmosphere
      - In phase – trough or ridge axes of two or more waves align (i.e. superimpose) themselves on each other.
        - » The trough or ridge amplifies due to constructive interference.

Atmospheric wave terminology

» This longitudinal “phasing” of major troughs or ridges in split jet stream flow often leads to sudden and dramatic increases in baroclinicity and storminess near the amplifying trough.

Atmospheric wave terminology

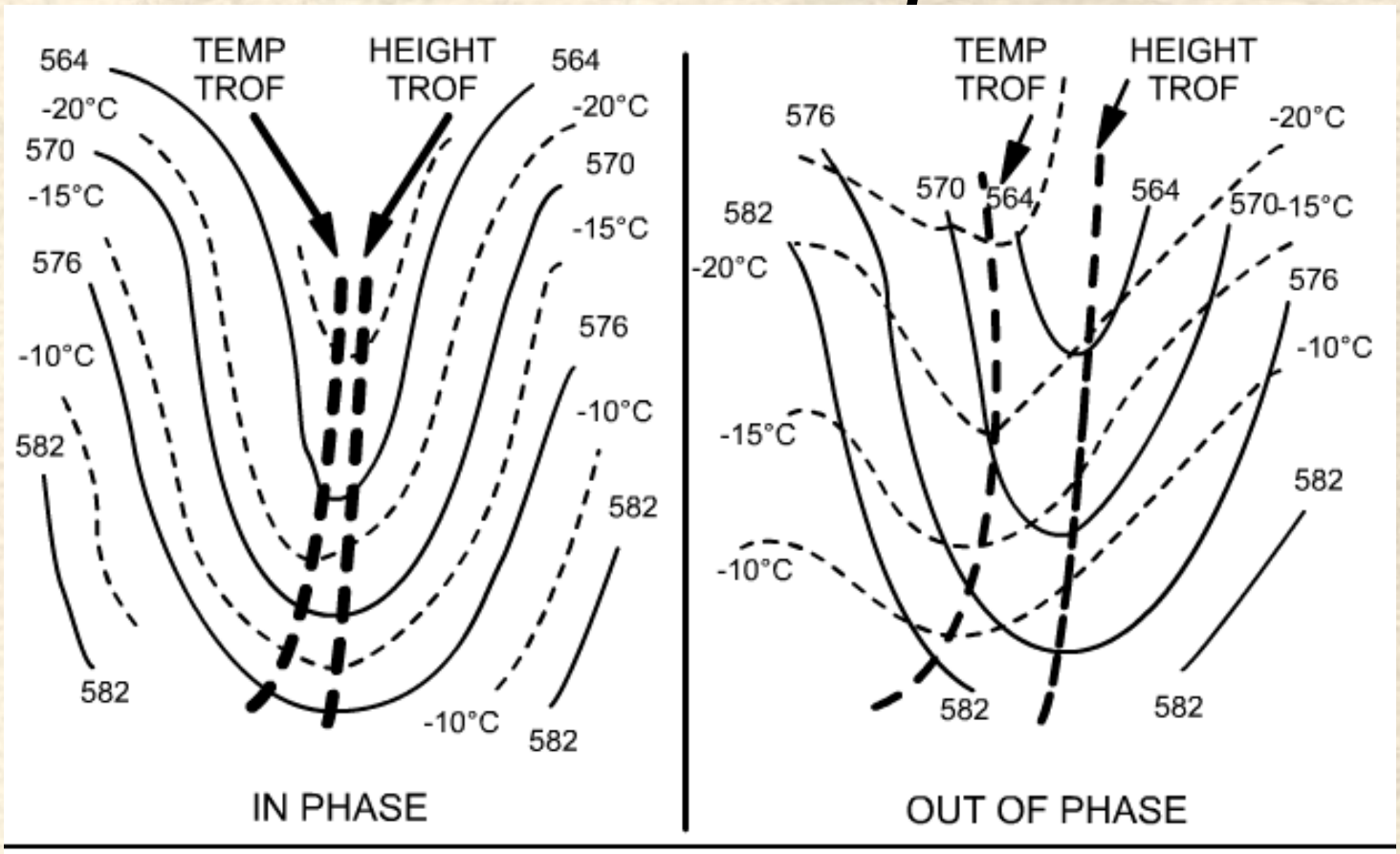
- Out of phase – trough or ridge axes of two or more waves become misaligned with each other.
  - » The trough or ridge deamplifies (I.e. damps) due to destructive interference
  - » This longitudinal damping of major troughs or ridges often leads to sudden and dramatic decrease in baroclinicity and storminess near the damping trough

Atmospheric wave terminology

– Height /temperature “ wave-axis/thermal-axis” relationships

- In phase - height ridges/troughs and thermal ridges/troughs nearly parallel. (Height contour and isotherm fields nearly parallel one another.)
- Out of phase - height ridges/troughs and thermal ridges/troughs **DO NOT** parallel. (Height contour and isotherm fields strongly intersect one another.)

Diagram, wave phase relationships



Barotropic vs. Baroclinic *Temperature and Height contour relationships:*

- Barotropic
  - The state of the atmosphere where temperature remains unchanged on isobaric (pressure) surfaces.
  - So, constant pressure maps(such as 850 mb or 500 mb) contain no isotherms or temperature gradients

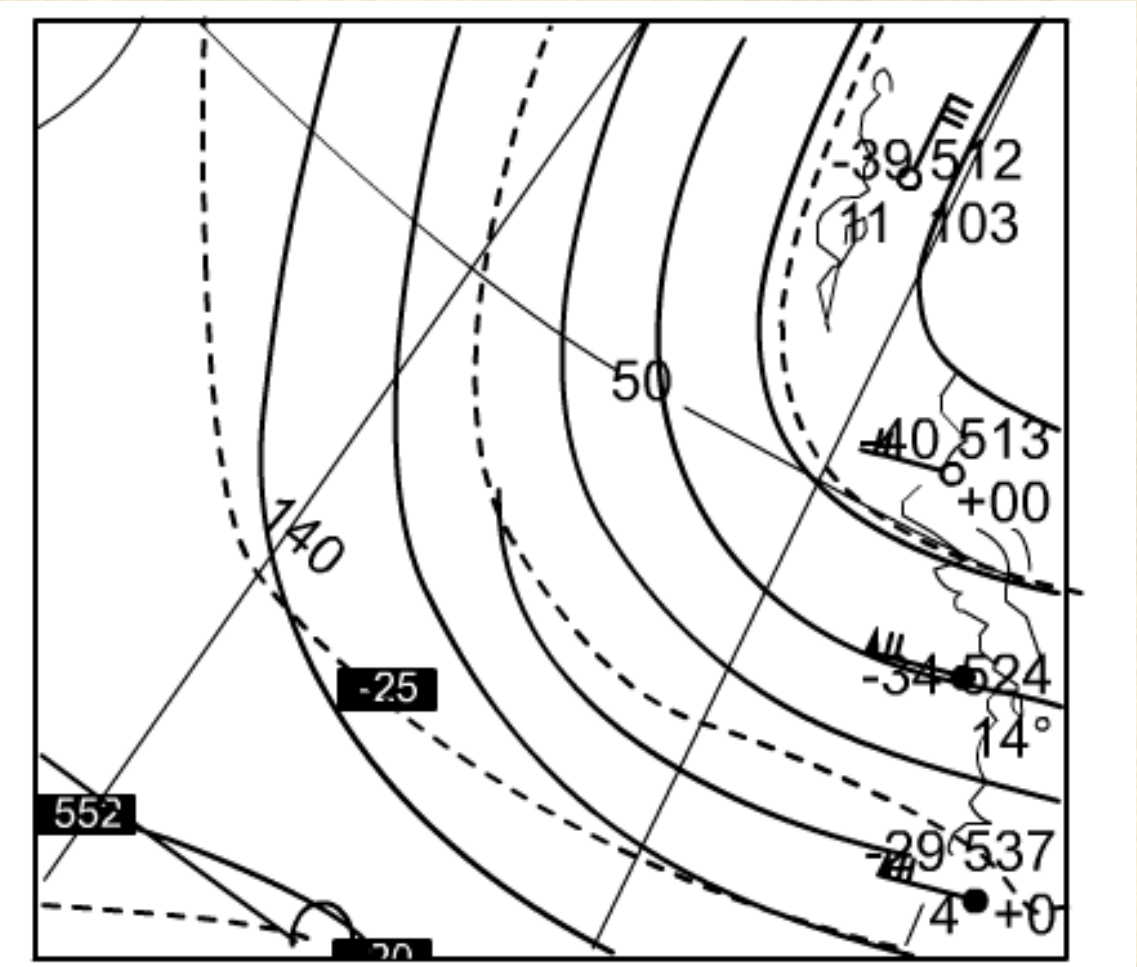
Barotropic vs. Baroclinic

- No vertical shear is allowed. Thus, no change in wind speed or direction with height is allowed.
  Thus, no thermal wind is allowed.

Barotropic vs. Baroclinic

- Barotropic atmospheres are very rare in the real atmosphere, but are most likely in the deep tropics.

Barotropic condition



Barotropic vs. Baroclinic

- Equivalent Barotropic (everyday term - barotropic)
  - The state of the atmosphere where isotherms can exist on isobaric charts, but these isotherms are parallel the height contours (i.e., isotherms and height contours are “in phase” with one another.)
  - Vertical shear is allowed. However, only wind speed may change with height, direction must be constant at each level (i.e. no veering or backing).

Barotropic vs. Baroclinic

– Thus,
a thermal wind is present, but no tem perature advection is allowed
.

Barotropic vs. Baroclinic

– Equivalent barotropic atmospheres frequently occur in the mid-latitudes.

Barotropic vs. Baroclinic

- Baroclinic
  - The state of the atmosphere where isotherms exist on isobaric charts and these isotherms intersect the height contours (i.e., isotherms and height contours are “out-of-phase” with one another.)
  - Vertical shear is allowed. Wind direction changes, and is usually accompanied by speed changes.

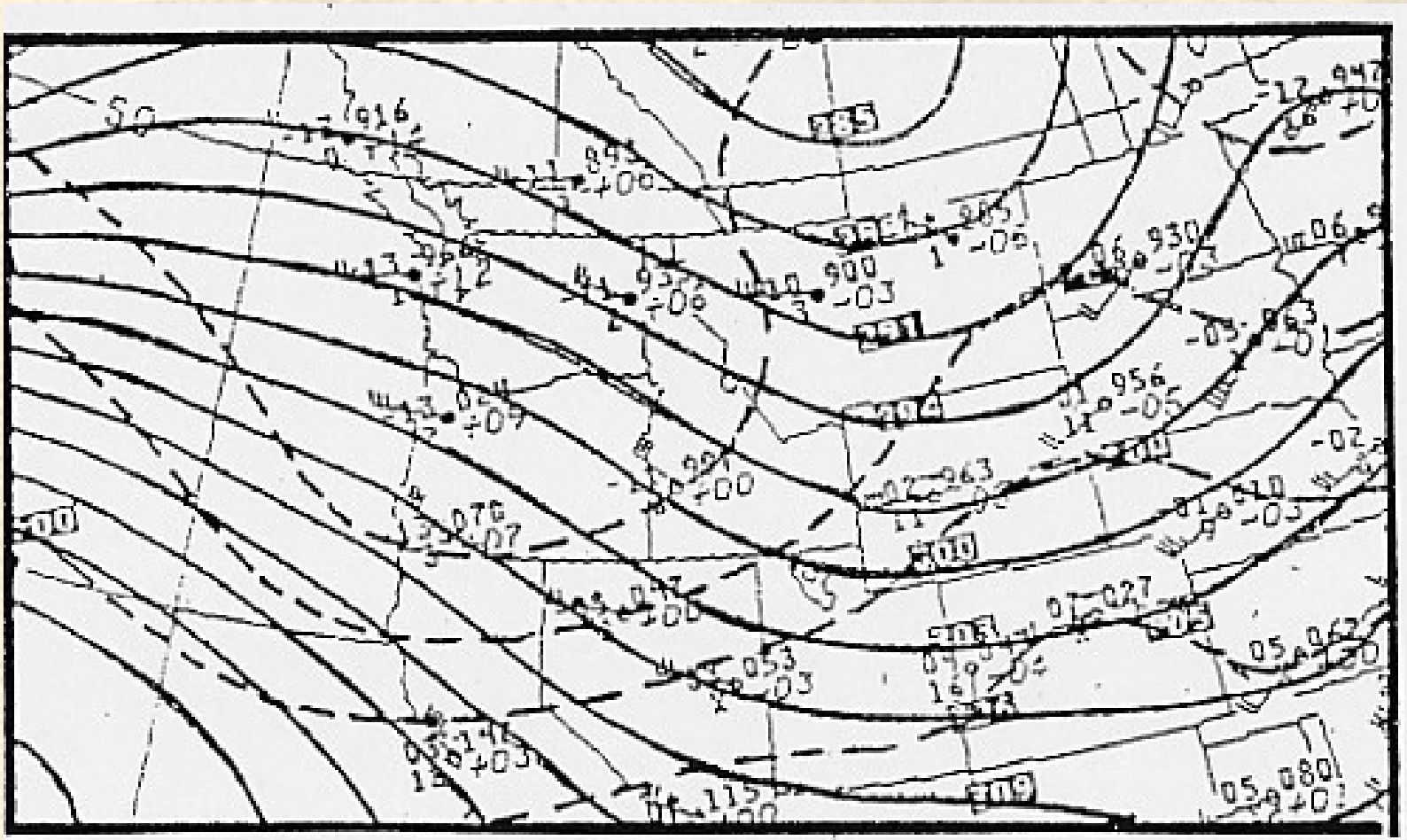
Barotropic vs. Baroclinic

- A thermal wind is present and temperature advection is allowed.

Barotropic vs. Baroclinic

- A baroclinic atmosphere is the most common condition observed in the mid-latitudes.

Baroclinic condition



Long waves

- Natural large scale wave pattern in the westerlies
- Often known as “Rossby waves” or “planetary waves”.

Long waves

- Results from
  - The variation of Coriolis force with latitude
  - The variation of temperature between equator and pole

Long waves

- Conservation of absolute vorticity in the mid-latitude westerlies.
  - An air parcel's absolute vorticity (η) cannot change as it moves through the atmosphere. Thus, η is constant.
  - Remember, the absolute vorticity (η) equals the sum of the relative vorticity (ζ) and the planetary vorticity (f): $\eta = \zeta + f$

Long waves

- Since η = constant, then $\eta = \zeta + f$ = constant, so $\zeta + f$ = constant. Rearranging:

  ζ = constant - f

  So, $\zeta \propto -f$ (i.e., ζ is inversely proportional to f)

  - If an air parcel's latitude is constant, then f is unchanged and ζ is constant (assume $\zeta = 0$).
  - If latitude decreases (i.e., the parcel moves closer to the equator), then f decreases and ζ must increase (i.e, cyclonic vorticity must increase as parcels move south).

Long waves

- If latitude increases (i.e., the parcel moves closer to the pole), then f increases and ζ must decrease accordingly (i.e, anticyclonic vorticity must increase as parcels move north).

Long waves

- In a Rossby wave, as air moves southeastward f decreases, forcing cyclonic vorticity to increase and forcing the parcel to move cyclonically at lower latitudes, hence forcing a trough in the lower latitudes.

Long waves

- In a Rossby wave, as air moves northeastward after passing the trough axis, f increases, forcing cyclonic vorticity to decrease and forcing the parcel to move anticyclonically at higher latitudes, hence forcing a ridge in the higher latitudes.

Long waves

- This cyclonic/anticyclonic oscillation of air parcels as they move equatorward/poleward/equatorward/pole ward describes the alternating trough/ridge/trough/ridge pattern seen in the mid-latitude westerlies.

PPT: Rossby (i.e. longwave) pattern showing a parcel's variation in ζ and f as it moves through the wave pattern.

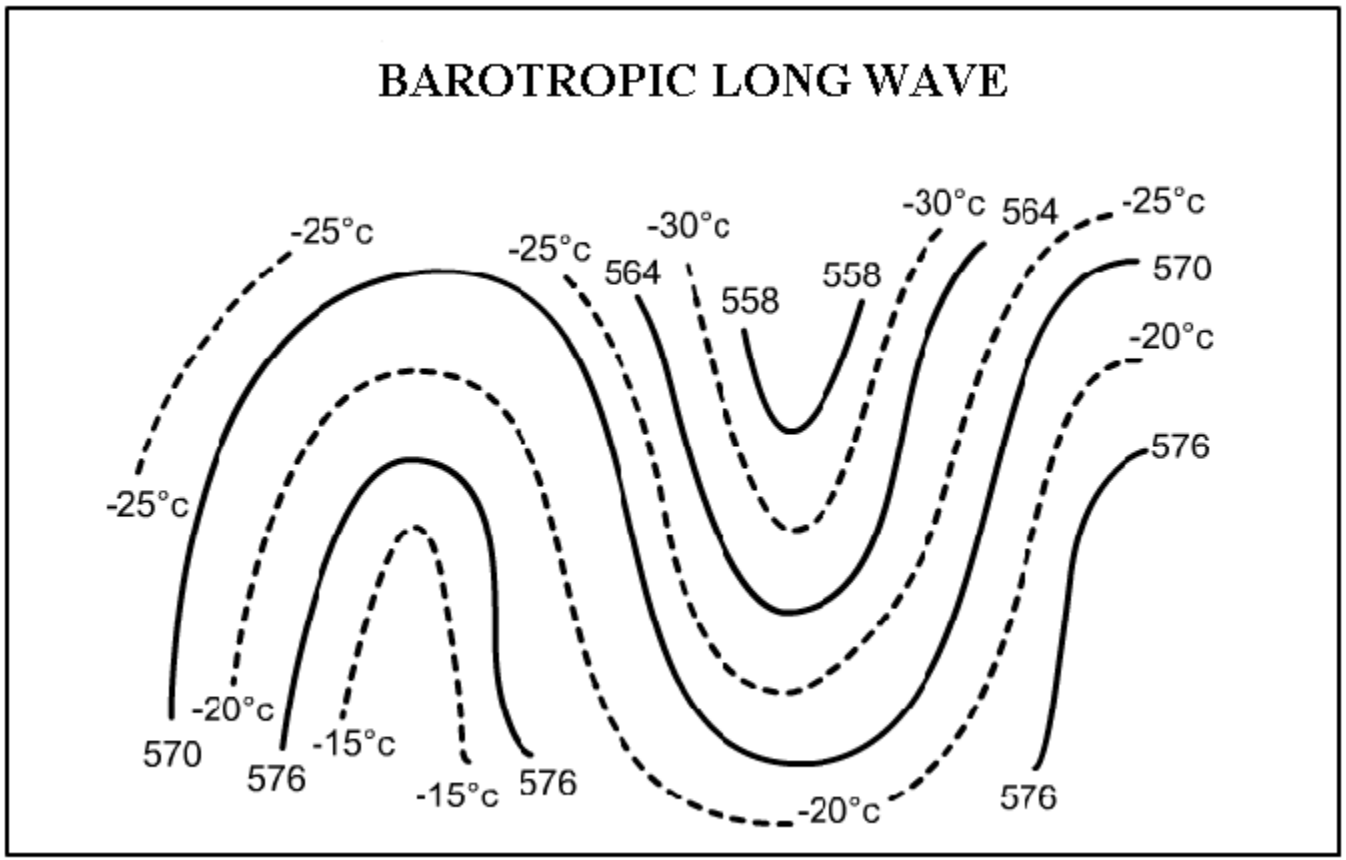
Long waves

- Climatological positions and amplitudes are influenced by:
  - Oceans
  - Land masses
  - Terrain features (such as mountain ranges)
- Axis of PFJ outlines the longwave pattern.

Long waves

- Characteristics of long waves
  - Equivalent Barotropic
    - Thermal/contour trough axes in phase.
    - Thermal/contour ridge axes in phase.
    - Longwave troughs - cold centers
    - Longwave ridges - warm centers.

Barotropic long wave



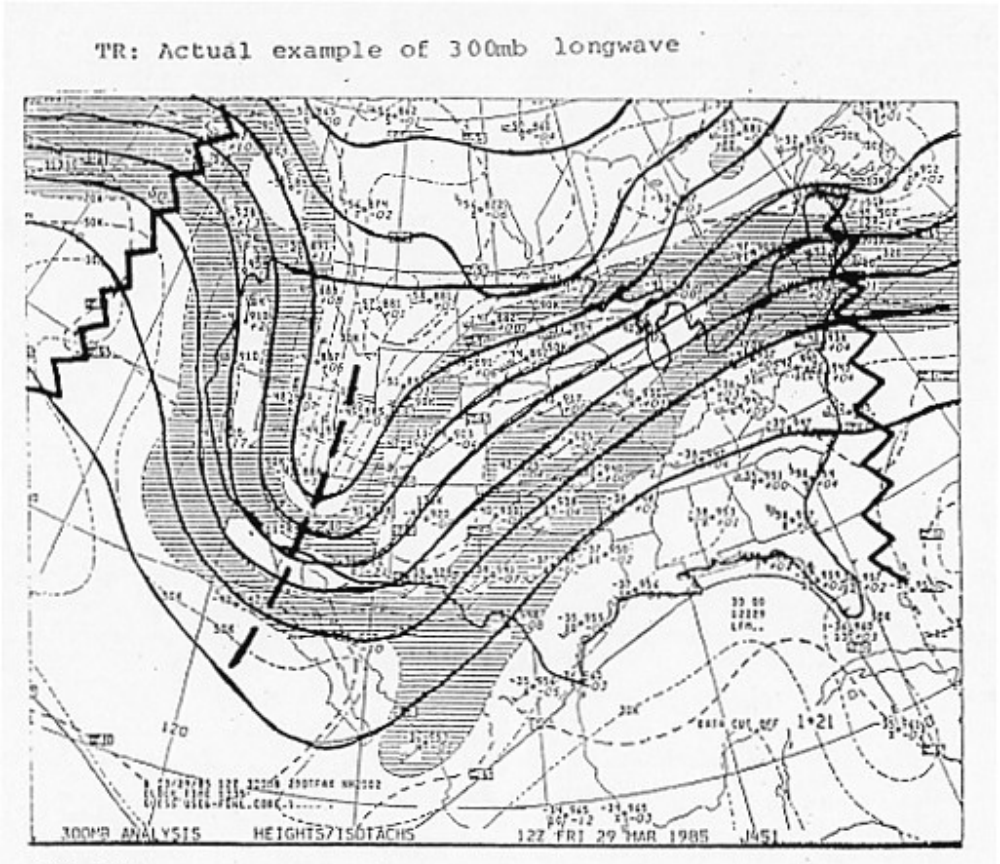
Long waves

- Troughs and ridges display very little vertical tilt (i.e., they are vertically stacked).

Long waves

- Best seen at 300-200-mb level, because the effects of smaller scale waves or eddies decrease**s** with height above mid levels in the troposphere.

Actual example of 300 mb - 200 mb longwave (need better figure)



Long waves

- Wavelength: 60° to 180° of longitude.
- Wave number:
  - Varies with the season
  - The number of waves per hemisphere ranges from 2 to 6. (typically 4 to 5)
  - Tend to be more waves in winter.

Long waves

- The smaller the number of waves
  - Larger the wavelength
  - Generally, the larger the amplitude.

- The larger the number of waves
  - Smaller the wavelength
  - Generally, the smaller the amplitude.

Long waves

– Wave speed:

- They generally progress slowly
- **ONLY** longwaves can remain stationary or retrogress in the westerlies.

Long waves

- Zonal index:
  - Definition -Measure of the strength of west to east component of the mid-latitude westerlies.
  - Best determined using a 500-mb hemispheric chart.

Long waves

- Zonal flow
  - Basic flow - west to east
  - Little north to south energy (heat and moisture) transfer occurs.
  - Large north to south temperature variations quickly develop.
  - Small west to east temperature variations.

Long waves

- Minimal phasing of waves.
- Weather systems tend to be weak and move rapidly from west to east

Long waves

- Meridional flow
  - Basic flow - north to south
  - Large-scale north-south energy transfer occurs.
  - North to south temperature variations quickly weaken.
  - Large west to east temperature variations.
  - Weather systems are often strong, with cyclones, producing large cloud and precipitation shields.

Long waves

- Locating long waves on the 500 mb hemispheric chart
  - long-wave pattern distorted due to **numerous** short waves.
  - a smoothed (filtered) 500 mb hemispheric chart works best since short waves have been removed (filtered out).

Long waves

- Check wave continuity on hemispheric charts for several days to determine the true position of the long-wave troughs and ridges

Long waves

- The importance of long waves
  - Defines the average jet stream location and storm track along the polar front
  - Long waves move cold air equatorward and warm air poleward in an attempt to balance the distribution of energy/heat in the atmosphere.

Long waves

- Determines the weather regime a location will experience over several days or possibly weeks.

Long waves

- Gradient wind relationship enhances vertical motion in the wave pattern.
  - Divergence and lifting is favored downstream of longwave trough or upstream of longwave ridge axes. Storminess is favored here.
  - Convergence and subsidence is favored upstream of longwave trough or downstream of longwave ridge axes. Clear skies are favored here.

Short waves

- Small atmospheric waves with wavelengths less than 3000 km.

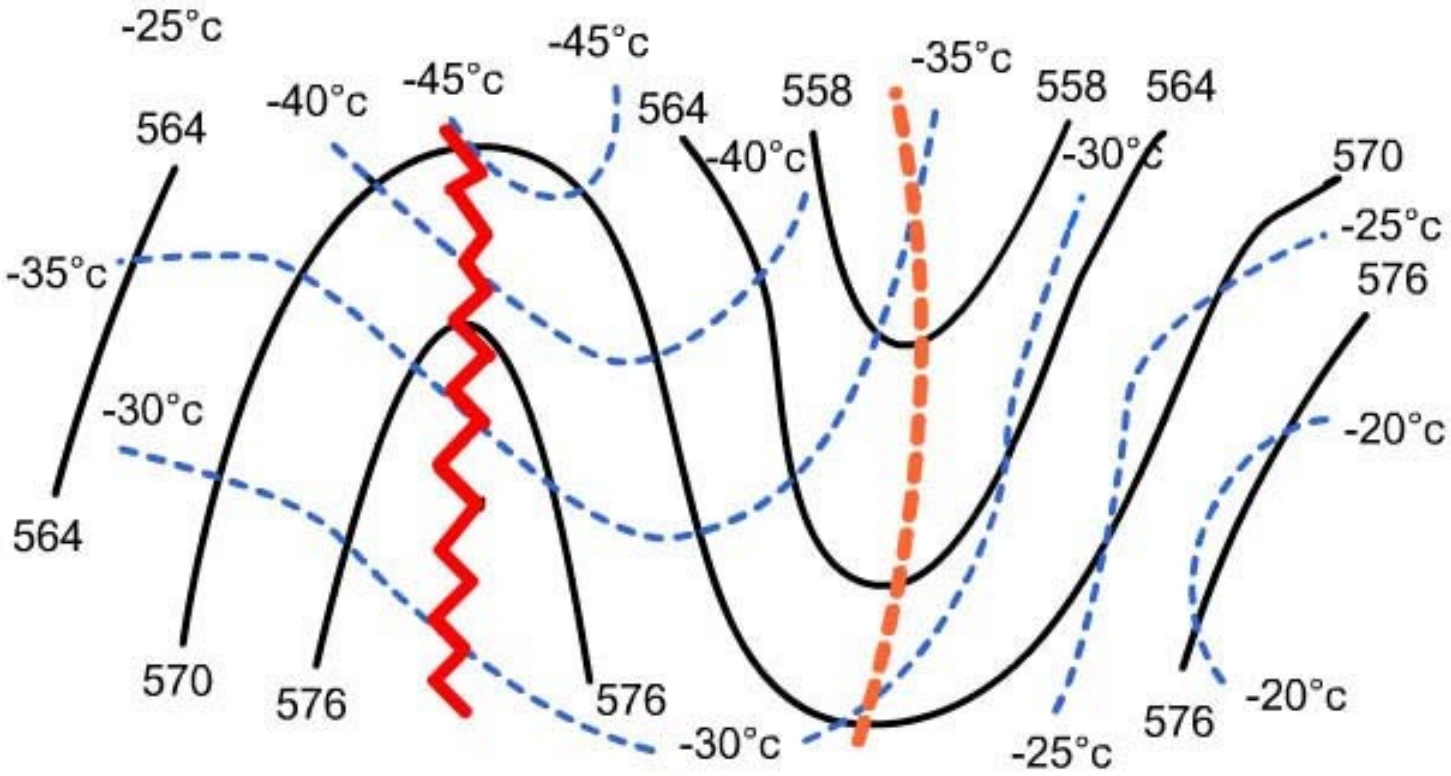
Short waves

- Also called baroclinic waves, they are associated with:
  - Temperature advection
  - Increased baroclinicity
  - Transient baroclinic cyclones and anticyclones

Short waves

- Form as result of baroclinic instability associated with the thermal wind and jet stream.
  - Short waves develop within the long-wave pattern as a result of this smaller scale instability.

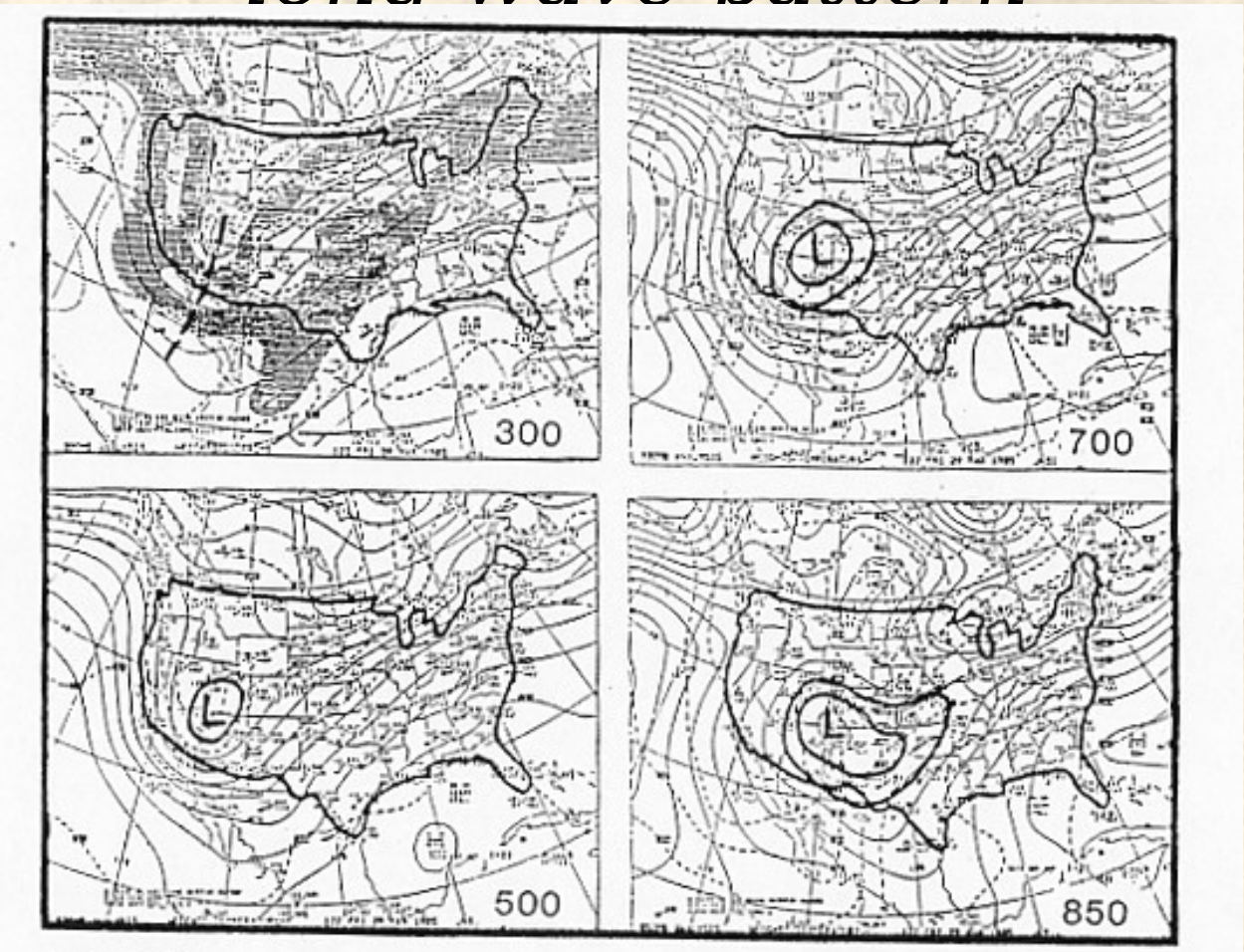
BAROCLINIC SHORT WAVE



Short waves

- Baroclinic
  - Isotherms / height contours out of phase, often resulting in strong temperature advection
  - 700-mb and 500-mb chart(s) most accurately depict actual location/intensity of short waves.
  - Typically contours/isotherms become more in phase above 500 mb.

Actual example of 700 mb, 500 mb with 300 mb showing relationship to lona-wave pattern



Short waves

- Wavelength - generally less than 30°.
- Wave speed:
  - Shortwaves prograde rapidly in fast westerlies
    - The westerlies are stronger in the winter; thus faster shortwave propagation is possible.

Short waves

– Given the same westerly flow, smaller shortwaves prograde faster than larger shortwaves.

Short waves

- Waves always move slower than the winds in which they are embedded.
  - For example, a shortwave moves eastward at say 50 or 60 knots, but it is embedded in say 100 knot winds. Thus, the winds are “blowing through” the wave.

Short waves

- Vertical profile
  - Baroclinic shortwaves tilt vertically, generally in a westward direction (i.e., tilt westward with increasing height).
    - shortwave troughs tilt vertically toward lower thickness (i.e., colder air).
    - shortwave ridges tilt vertically toward higher thickness (i.e., warmer air).

Short waves

- Shortwave troughs tilt from warm surface lows generally westward toward cold upper-level troughs.
- Shortwave ridges tilt from cold surface highs generally westward toward warm upper-level ridges.
- Thus, as shortwave trough/ridge axes tilt westward with height, the thermal trough/ridge tilts eastward. This means height and temperature fields are vertically out of phase in baroclinic shortwaves (just as they are out of phase horizontally).

Short waves

- Types of short waves
  - Major shortwave -
    - Shortwave large enough to significantly distort longwave pattern.
    - Reflected through large depth of atmosphere.
    - Shortwaves may amplify or phase and become a longwave, thus changing the number of longwaves. Behavior will change accordngly (i.e., slower motioin, change from baroclinic to equvalent barotropic, etc…)

Short waves

- Minor short waves
  - Small short wave
  - Generally moves faster than major short wave
  - Causes very little distortion to longwave pattern.
  - May only extend through a shallow depth of the troposphere and sometimes is only reflected at one level.

Short waves

- Methods of locating shortwaves:
  - Turning of wind flow and/or height contours on an isobaric surface.
    - Trough – cyclonic turning
    - Ridge – anticyclonic turning

Short waves

- Height changes on the constant pressure (isobaric) charts.
  - Trough: Thermal trough (associated with CAA) found alone (No cyclonic turning) in the contour flow may be evident. Beware that cyclonic turning will not be evident in many smoothed computer analyses.
    - Generally, height falls (or sometimes small rises) near and downstream of shortwave axis
    - Generally, height rises (or sometimes small falls) near and upstream of shortwave axis.

Short waves

- Ridge
  - Generally, height rises (or sometimes small falls) near and downstream of shortwave axis
  - Generally, height falls (or sometimes small rises) near and upstream of shortwave axis

Short waves

- Trough: Thermal trough (associated with CAA) found alone (No cyclonic turning) in the contour flow may be evident. Beware that cyclonic turning will not be evident in many smoothed computer analyses.

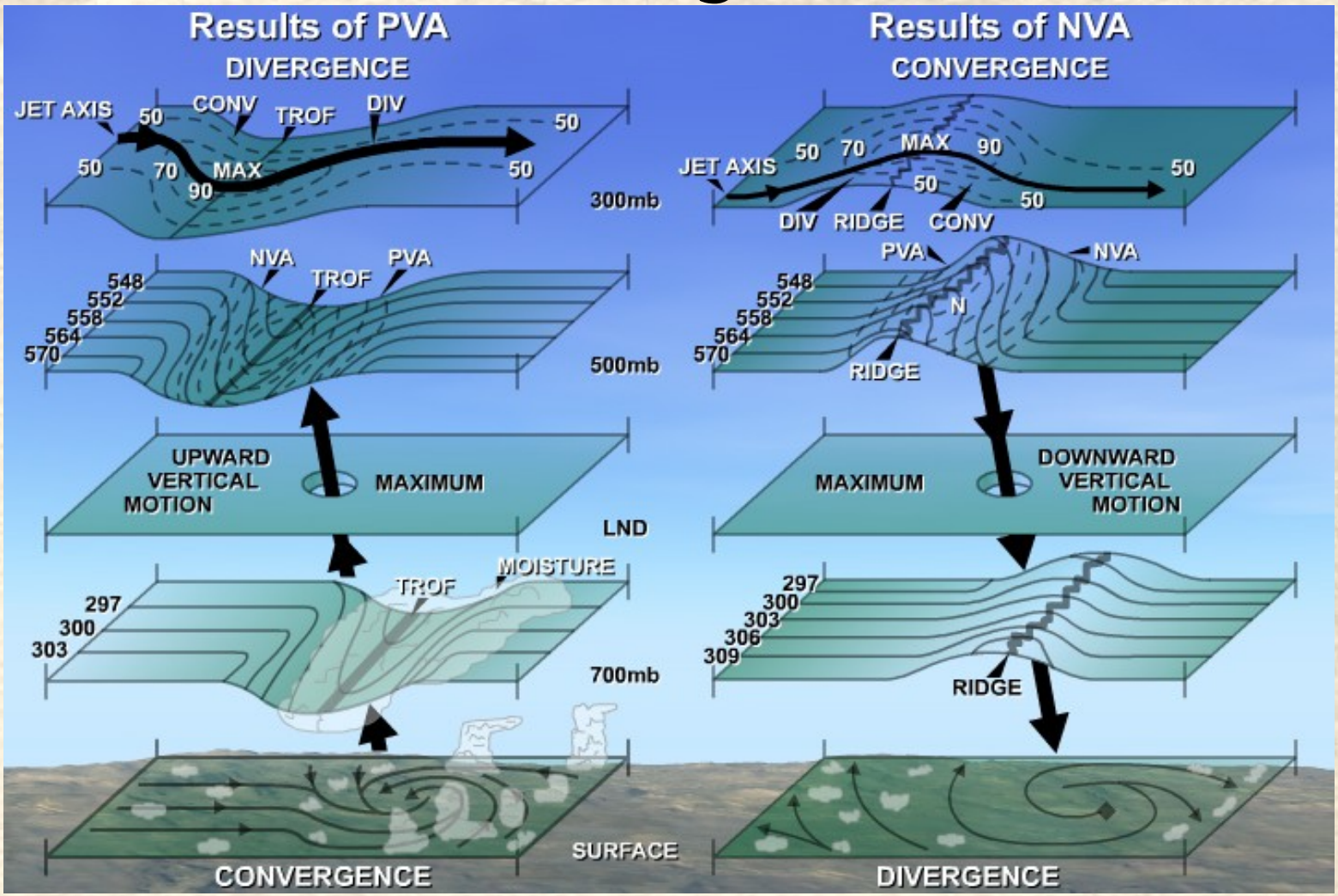
Short waves

– Vorticity is also good indicator of the location of shortwaves (discussed in detail in following section).

Short waves

- Stacking - Major shortwaves exhibit a tilted stack (generally toward the west, northwest, or southwest with height). For troughs:
  - Down toward the warmest air at lower levels. For example:
    - Moving down from the 500-mb trough axis to the associated surface low, the frontal system near the low may be located a few degrees of latitude toward the warmer air.
    - Associated 700 and 850-mb troughs generally fall between the 500 mb trough and surface cyclone positions.
  - Up toward the colder air at higher levels in the troposphere.

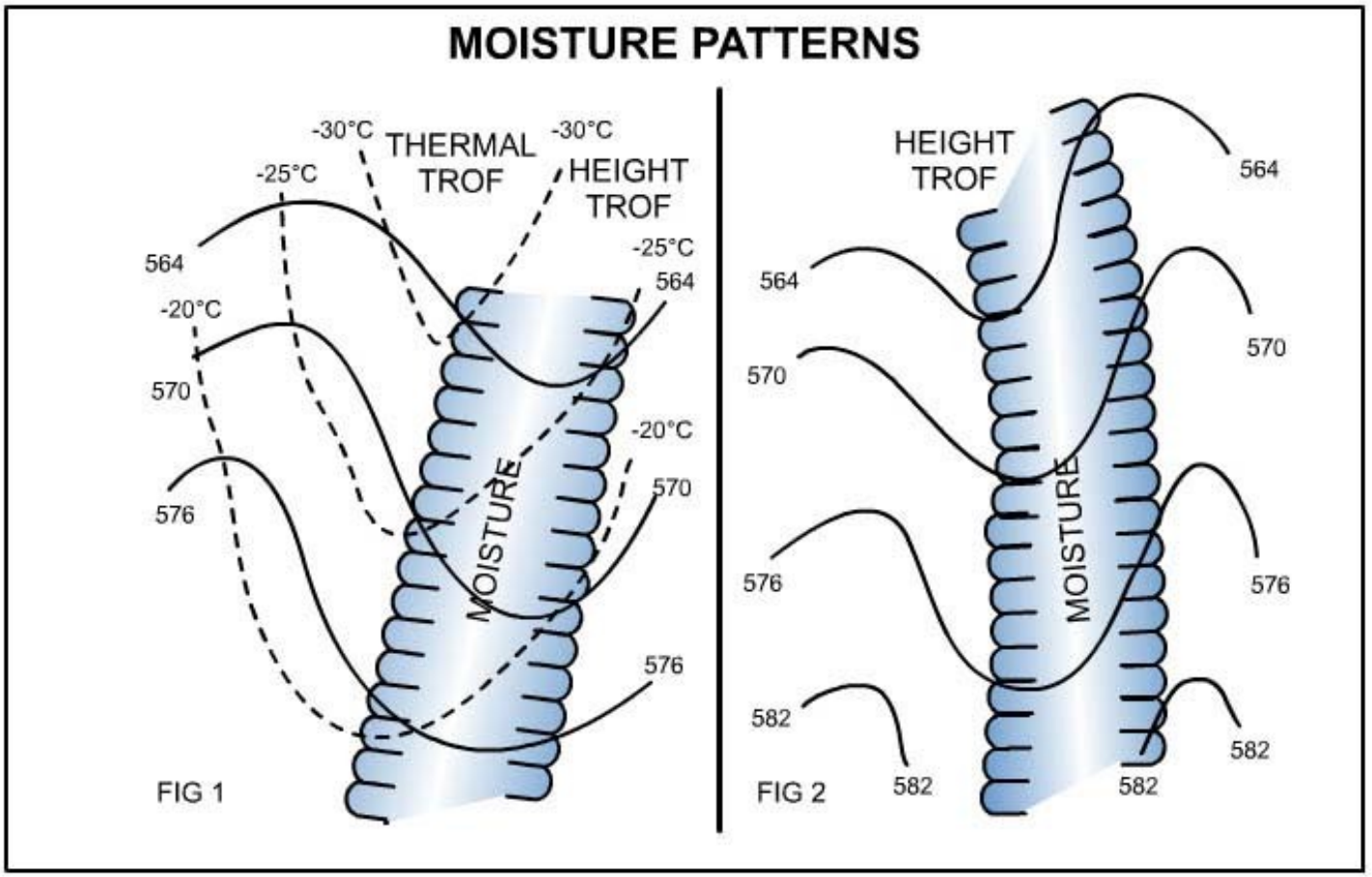
Vertical Stacking of shortwave trough



Short waves

- Continuity
  - Shortwave's movement determined by keeping track of the previous position of its axis from chart to chart.
  - Provides a good indication of **where** it could be on the next chart. (Extrapolation)
- Moisture
  - Areas of moisture common ahead of or centered on trough axis
  - Look for areas with dew point depressions of $\leq 5^{\circ}C$

Moisture patterns



Short waves

- May extend upstream to thermal trough axis,
- The more baroclinic the short wave the more extensive the moisture field can be.
- May extend downstream from the trough to a sharp (high amplitude) ridge axis and over a weaker (lower amplitude) ridge axis.
- Nearly saturated mid-tropospheric conditions many times indicates lifting

Short waves

- Extreme dryness is common behind trough axis and sometimes crossing east of the trough axis in a “dry tongue” along the jet core. (Easily identifiable in water vapor satellite imagery.)
- Look for areas with dew point depressions > 20°C. (Note, this is an arbitrary threshold)
- Very dry mid-tropospheric conditions many times indicate subsidence

Intermediate Waves

- Waves with wavelengths in between longwaves and shortwaves
- Intermediate waves may act more like a longwave than a shortwave, or vice versa, depending on the situation.
- These waves must be evaluated on a case by case basis.

- **APPLICATION: Review Exercise in Student Text**
- **EVALUATION:**
  - **Informal: Appraisal**
  - **Formal: Written Test**